



## **A new generation of satellite based solar irradiance calculation schemes**

R.W. Mueller, Detlev Heinnemann, Carsten Hoyer, R. Kuhlemann, Knut-Frode Dagestad, Jan Olseth, Arvid Skarveit, Sylvain Cros, Lucien Wald, Marion Schroedter Homscheidt, et al.

### **► To cite this version:**

R.W. Mueller, Detlev Heinnemann, Carsten Hoyer, R. Kuhlemann, Knut-Frode Dagestad, et al.. A new generation of satellite based solar irradiance calculation schemes. 22nd EARSeL Annual Symposium "Geoinformation for European-wide integration", Jun 2002, Prague, Czech Republic. pp.201-208. hal-00465102

**HAL Id: hal-00465102**

**<https://hal-mines-paristech.archives-ouvertes.fr/hal-00465102>**

Submitted on 28 Feb 2014

**HAL** is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.

# A new generation of satellite based solar irradiance calculation schemes

R. W. Mueller, D. Heinemann, C. Hoyer & R. Kuhlemann

*Energy-Meteorology group, University of Oldenburg, Germany*

K.F. Dagestad, J.A. Olseth & A. Skartveit

*Geophysical Institute, University of Bergen, Norway*

S. Cros, L. Wald

*Remote Sensing and Modeling Group, Ecole des Mines de Paris, France*

M. Schroedter

*Remote Sensing Data Center, German Aerospace Center, Germany*

D. Dumortier

*Ecole Nationale des Travaux Publics de l'Etat, France*

P. Ineichen

*Groupe de Physique Appliqué - Energie (UNIGE), University of Geneva, Switzerland*

C. Piernavieja

*Instituto Tecnológico de Canarias, Spain*

**Keywords:** radiative transfer, solar irradiance, MSG

**ABSTRACT:** A successful integration of solar energy into the existing energy structure highly depends on a detailed knowledge of the solar resource. HELIOSAT-3 will supply high-quality solar radiation data gained from the exploitation of existing Earth observation technologies and will take advantage of the enhanced capabilities of the new Meteosat Second Generation (MSG) satellites. The expected quality represents a substantial improvement with respect to the available methods and will better match the needs of companies and other customers of the resulting products. These goals will be achieved by an improvement of the current semi-empirical Heliosat calculation schemes (see section 2) as well as by the development and establishment of a new type of calculation scheme. This new type will be based on radiative transfer models (RTM) using the information of atmospheric parameters retrieved from the MSG satellite (clouds, ozone, water vapor) and the GOME/ATSR-2 satellites (aerosols). Within this paper, the new type of the solar irradiance calculation scheme, including the functional treatment of the diurnal variation of the solar irradiance, is described.

## 1 INTRODUCTION

Remote Sensing from satellites is a central issue in monitoring and forecasting the state of the earth's atmosphere. Geostationary satellites such as METEOSAT provide cloud information in a high spatial and temporal resolution. Such satellites are therefore not only useful for weather forecasting, but also for the estimation of solar irradiance since the knowledge of the light reflected by clouds is the basis for the calculation of the transmitted light. Additionally a detailed knowledge about atmospheric parameters involved in scattering and absorption of the sunlight are necessary for an accurate calculation of the solar irradiance. An accurate estimation of the downward solar irradiance is not only of particular importance for the assessment of the radiative forcing of the climate system, but also absolutely necessary for an efficient planning and operation of solar energy systems.

Currently, most of the operational calculation schemes

for solar irradiance are semi-empirical, based on statistical methods. They use cloud information from the current METEOSAT satellite and climatologies of atmospheric parameters e.g. turbidity (aerosols and water vapor). The Meteosat Second Generation satellite (MSG, to be launched in 2002) will provide not only a higher spatial and temporal resolution, but also the potential for the retrieval of atmospheric parameters such as additional cloud parameters, ozone, water vapor column and with restrictions aerosols.

Using the enhanced capabilities of the new MSG satellite, solar irradiance data with a high accuracy, a high spatial and temporal resolution and a large geographical coverage will be provided, within the EU funded project HELIOSAT-3.

This is clearly related to the needs of solar energy applications. The expected quality of the solar irradiance data will represent a substantial improvement with respect to the available methods and will better match the

needs of customers of the resulting products.

These goals will be achieved by an improvement of the current semi-empirical Heliosat calculation scheme (see section 2) as well as by the development and establishment of a new type of calculation scheme (see section 3). This new type will be based on radiative transfer models (RTM) using the information of the atmospheric parameters retrieved from the MSG satellite (clouds,  $O_3$ , water vapor) and the GOME/ATSR-2 satellites (aerosols,  $O_3$ ).

It is expected that the MSG data in combination with the new calculation scheme will increase significantly the accuracy of the calculated surface solar irradiance. Other benefits will be the high spectral resolution, the enhanced information about spatial structure of solar irradiance and angular distribution of the diffuse light.

In order to enable a better understanding of the new scheme the current scheme is described in the next section. Afterwards the new solar irradiance calculation scheme, including the functional treatment of the diurnal variation of the solar irradiance, is described. The improvements linked with the adaption of the new calculation scheme are discussed taking into account principle benefits and limitations of the new method.

## 2 The current HELIOSAT scheme

The general idea of the method is to deal with atmospheric and cloud extinction separately. In a first step a cloud index is derived from METEOSAT imagery. This step uses the fact that the planetary albedo measured by the satellite is proportional to the amount of cloudiness. The derived cloud index is then correlated to the cloud transmission. The clear-sky irradiance is then diminished by the cloud transmission to infer the ground irradiance. For this second step a clear sky model is necessary in order to calculate the clear-sky irradiance for a given location and time is calculated. The two modules are described below.

### 2.1 Cloud Transmission

Clouds have the largest influence on atmospheric radiative transfer. The cloud amount is derived from METEOSAT imagery. At the beginning the METEOSAT images have to be normalized with respect to the solar zenith angle. Therefore the relative reflectance  $\rho$  is introduced:

$$\rho = \frac{C - C_0}{G_{ext}}. \quad (1)$$

Here  $C$  is the measured value of the satellite pixel and  $C_0$  is the instrument offset. Since  $G_{ext}$  is used,  $\rho$  is a measure of the planetary albedo. Originally  $C_0$  was considered as a constant. Beyer et. al (1996) split this off-

set into an instrument offset  $C_{off}$  and atmospheric offset  $C_{atm}$  which is due to backscatter of the atmosphere.  $C_{atm}$  was derived by an analysis of ocean pixels:

$$C_{atm} = (1 + \cos^2 \Psi) \cdot \frac{f(\theta_z)}{\cos^{0.78} \phi}, \quad (2)$$

where  $\Psi$  is the angle between sun and satellite as seen from the ground,  $\phi$  the zenith angle of the satellite and  $\theta_z$  the solar zenith angle (SZA). The function  $f(\theta_z)$  is defined as:

$$f(\theta_z) = -0.55 - 25.2 \cdot \cos \theta_z - 38.3 \cdot \cos^2 \theta_z + 17.7 \cdot \cos^3 \theta_z. \quad (3)$$

The cloud index is a measure of the cloud cover, it varies between 0 for no clouds and 1 for full cloud cover. It is calculated using the reflectivity  $\rho$  from equation 1:

$$n = \frac{\rho - \rho_{min}}{\rho_{max} - \rho_{min}}. \quad (4)$$

To calculate  $n$ , the maximum  $\rho_{max}$  and minimum  $\rho_{min}$  values of  $\rho$  are needed.  $\rho_{min}$  corresponds to the ground albedo. Maps of the ground albedo are computed on a monthly basis by statistical analysis of the dark pixels. The maximum reflectivity  $\rho_{max}$  has to be computed once per satellite since there are differences in the sensor properties in the different METEOSAT satellites (Hammer et. al, 2001)

Cloud transmission can be described as seen from the ground by the clear-sky index  $k$  which compares the actual ground irradiance  $G$  with the irradiance of the cloud free case  $G_{clearsky}$ :

$$k = \frac{G}{G_{clearsky}}. \quad (5)$$

The cloud index is then empirically correlated to the clear sky index  $k_T^*$ . This relationship is basically  $k_T^* = 1 - n$  with minor modifications for  $n \rightarrow 0$  and  $n \rightarrow 1$ :

$$\begin{aligned} n \leq -0.2 & \quad k = 1.2 \\ -0.2 < n \leq 0.8 & \quad k = 1 - n \\ 0.8 < n \leq 1.1 & \quad k = 2.067 - 3.667 \cdot n + 1.667 \cdot n^2 \\ 1.1 < n & \quad k = 0.05 \end{aligned} \quad (6)$$

The ground irradiance  $G$  is obtained from

$$G = k \cdot (G_{direct,clearsky} \cdot \cos \theta_z + G_{diffus,clearsky}) \quad (7)$$

### 2.2 The current Clear-Sky Model

The HELIOSAT-Method was originally proposed by Cano et. al (1986) and later modified by Beyer et. al (1996) and Hammer (2000). For the calculation of the

clear sky irradiance it uses the direct irradiance model of Page (1996) and diffuse irradiance model of Dumortier (1995). Both use the Linke turbidity factor to describe the atmospheric extinction. The direct irradiance is:

$$G_{direct,clearsky} = G_0 \cdot \epsilon \cdot e^{-0.8662 \cdot T_L(2) \cdot \delta_R(m) \cdot m} \quad (8)$$

where  $G_0$  is the extraterrestrial irradiance,  $\epsilon$  the eccentricity correction,  $T_L(2)$  the Linke-Turbidity factor for airmass 2,  $\delta_R(m)$  the Rayleigh optical thickness and  $m$  the airmass. In a plane parallel atmosphere the air mass would be easy to obtain geometrically through the cosine of the solar zenith angle (SZA)  $\theta_z$ :

$$m = \frac{1}{\cos \theta_z}. \quad (9)$$

Since the atmosphere is not plane parallel, the following relation developed by Kasten and Young (1989) is used:

$$m = \frac{1 - z/10000}{\cos \theta_z + 0.50572(96.07995^\circ - \theta_z)^{-1.6364}} \quad (10)$$

using  $z$  as the height in meters and the SZA  $\theta_z$  in degrees. The Rayleigh optical thickness  $\delta_R(m)$  is the optical thickness of a dry and clean atmosphere, an atmosphere without aerosols and water vapor, where only Rayleigh scattering occurs.

The Linke-Turbidity is defined as the number of Rayleigh atmospheres one would need to represent the real optical thickness  $\delta(m)$ :

$$T_L(m) = \frac{\delta(m)}{\delta_R(m)} \quad (11)$$

Since this turbidity still has a daily variation, it is normalized to the turbidity for the airmass 2:

$$T_L(2) = \frac{T_L(m) \cdot \delta_R(m)}{\delta_R(2)}. \quad (12)$$

The diffuse irradiance is an empirical fit by Dumortier (1995)

$$G_{diffus} = G_0 \cdot \epsilon \cdot \cos \theta_z^2 \cdot (0.0065 + (-0.045 + 0.0646 \cdot T_L(2)) \cdot \cos \theta_z + (0.014 - 0.0327 \cdot T_L(2))) \quad (13)$$

The spectral channels of METEOSAT cannot be used to derive information on the atmospheric turbidity. Therefore a climatological model must be used. To account for the annual variation of the turbidity a relation of Bourges (1992) is used:

$$T_L = T_0 + u \cos \left( \frac{2\pi}{365J} \right) + v \sin \left( \frac{2\pi}{365J} \right), \quad (14)$$

$T_0$ ,  $u$  and  $v$  are site specific fit parameters,  $J$  is the day of the year. A map with the parameters for Europe has been set up during the EU-funded Satel-Light project ([www.satellight.com](http://www.satellight.com)).

### 2.3 Direct and Diffuse Irradiance

So far we have found a way to calculate the global ground irradiance. For many applications like daylight or irradiance on tilted planes also the fraction of direct and diffuse irradiance has to be known.

The direct and diffuse component of the ground irradiance is then calculated using a statistical model of Skartveit et. al (1998). The model is based on hourly values of the global irradiance. It uses the clearness index  $k_T$ , the elevation of the sun and an hourly variability index  $\sigma_3$  for the calculation of the diffuse fraction.

The hourly variability index  $\sigma_3$  is calculated from the clear sky indices of three consecutive hours. If  $k_i$  is the clear-sky index of the hour  $i$  in question, then  $\sigma_3$  is defined as:

$$\sigma_3 = \sqrt{\frac{(k_i - k_{i-1})^2 + (k_i - k_{i+1})^2}{2}}. \quad (15)$$

## 3 THE NEW SCHEME

With the launch of the Meteosat Second Generation (MSG) satellite the possibilities for monitoring the earth atmosphere (especially for cloud description) will be enormously improved. The MSG weather satellite will provide not only a higher spatial and temporal resolution but will also scan the earth atmosphere with much more spectral channels than the current satellite. The improved spectral information is linked with the potential for the retrieval of atmospheric parameters such as ozone, water vapor and with restrictions aerosols as well as an improved description of clouds.

With this more detailed knowledge about atmospheric parameters we will establish a new calculation scheme based on a radiative transfer model (RTM) that uses the retrieved atmospheric parameters as input. This new scheme will be based on the integrated use of a radiative transfer model, whereas the information of the atmospheric parameters retrieved from the MSG satellite (clouds, ozone, water vapor) and e.g. from the GOME/ATSR-2 satellites (aerosols, ozone) will be used as input to the RTM based scheme.

The limitations of 3-d cloud modeling do not enable realistic RTM calculations of 3-d cloud problems in an operational manner, but just case studies, since

Table 1: Improvements in METEOSAT resolution

parameter	METEOSAT	MSG
spatial resolution (sub sat. point)	2.5 km	1 km
temporal resolution	30 min	15 min
spectral channels	3	12

the necessary 3-d cloud input information can (yet) not be provided operationally. Hence with respect to the use of a RTM the problem is the non-availability of realistic specification of heterogeneous clouds from measurements. MSG will not provide sufficient information about 3-d cloud characteristics. No other satellite or measurement setup provides this information for the needed temporal resolution and spatial coverage.

Beside these problems an explicit or integrated use of RTM is not possible since the needed calculation time of 3d-RTM models is too large for operational adaptation. With respect to the application of look-up tables, it has to be considered that there are infinite different 3-d cloud cases (states).

As a consequence of the things mentioned above, the usage of a RTM (whether directly or via the usage of pre-calculated look-up tables) is not reasonable with respect to heterogeneous clouds. Hence the integrated usage of the RTM within the scheme is related to the clear-sky scheme using the well established  $n-k$  relation (see formula 6) to consider cloud effects. Keeping in mind the problems of 3-d cloud modeling it is obvious that the usage of the  $n-k$  relation is not linked with a restriction with respect to the treatment of the heterogeneous clouds. The  $n-k$  relation is powerful and validated and leads to small Root Mean Square Deviation (RMS) between measured and calculated solar irradiance for almost homogeneous cloud situations.

Nevertheless the  $n-k$  relation can and will be improved within the HELIOSAT-3 project with respect to the following tasks.

- Within the HELIOSAT-3 project it has been showed that the cloud height in correlation with the geometry has an effect on the  $n-k$  relation. This is currently not considered within the already existing  $n-k$  relation, but will be considered in the new scheme.
- With MSG it is possible to retrieve cloud height information operationally, hence in contrast to the old Heliosat method "cloud shadowing" effects (for low solar elevations) will be considered within the new scheme.
- Heterogeneous cloud effects will be investigated in order to correct the  $n-k$  relation in a statistical manner e.g. improve the calculated relation between diffuse and direct light, using cloud height and a variability index to correct the  $n-k$  relation. This work will be based on previous studies of Skartveit et al. (1998), adapting a similar approach to the new scheme.

The forthcoming of this paper deals with the integrated use of the RTM within the scheme and hence focuses on the clear-sky module of the scheme.

### 3.1 The new clear-sky module

MSG will scan the earth atmosphere in a very high spatial resolution (see table 1, e.g. approximately 2.5 million pixels have to be processed every 15 min. for Europe). Thus the computing time necessary to calculate the solar irradiance for each pixel has to be very small to make an operational usage of the solar irradiance scheme possible.

One possibility to manage the computing time problem, with respect to RTM applications, is the use of look-up tables to consider the effect of atmospheric parameter on the solar irradiance. Instead of doing this a new more powerful and more flexible method, the integrated use of RTM within the scheme based on a modified Lambert-Beer relation, will be applied within the HELIOSAT-3 project.

The integration of RTM into the calculation schemes, instead of using just pre-calculated look-up tables, is only possible if the necessary computing time can be decreased enormously. For this purpose a tricky functional treatment of the diurnal solar irradiance variation has to be applied. Thus making an appropriate operational use of a RTM within the calculation schemes possible.

The basis (or starting point) of the integrated use is the assumption that daily values of the atmospheric parameters in a spatial resolution of 100x100 km (or 50x50 km) are sufficient. Relating to this assumption the following tasks have to be considered

- Daily values of ozone are not necessary (for our purposes) and a resolution of 100x100 km is more than sufficient, since the effect of  $O_3$  on the solar irradiance in the relevant wavelength region is small.
- H<sub>2</sub>O: Daily values are linked with a great improvement compared to the current implicit use of H<sub>2</sub>O within a monthly turbidity climatology. The direct effect of  $H_2O$  is small compared to the effect of aerosols and the retrieval is not possible for cloudy pixels. As a consequence daily averages are the most reasonable solution in consideration of accuracy and operational practicality.
- Aerosols have the largest effect on the solar irradiance. The art of Aerosol retrieval is characterized by some principal limitations/restrictions, (very small Aerosol reflectance and perturbation of the weak signal by clouds and surface reflection). Therefore retrieval of daily values in 100x100 km resolution with a "global" coverage in an appropriate accuracy is a task for the far future. daily values in such a spatial resolution would be fantastic. An accurate climatology with a monthly temporal and 100x100km spatial resolution will be the goal within the next years. E.g. with the usage of SCIAMACHY/AATSR a spatial resolution of 100x100km and monthly resolution is aimed for.

As a consequence of the facts mentioned above daily values of the atmospheric parameter ( $O_3, H_2O, \text{aerosols}$ ) with a 100x100 km (or 50x50) spatial resolution would be most sufficient for solar energy applications in consideration of accuracy and operational practicality. Hence the assumption that daily values of the clear sky atmospheric parameters are sufficient is not linked with restrictions of the model. Especially as the usage the modified Lambert-Beer law, described later on, enables the correction of derivations from the daily average in an easy manner (see also the conclusions).

Since daily values of the atmospheric parameters ( $O_3, H_2O, \text{aerosols}$ ) within a region of 100x100km (50x50km) can be assumed as sufficient the diurnal variation of the solar irradiance is just dependent on the Solar Zenith Angle (SZA,  $\theta_z$ ). The RTM calculates the diurnal variation of the solar irradiance for this region using the averaged atmospheric parameters as input. Within this region a specific SZA belongs to each scanned pixel with respect to its time and location. The corresponding value of the solar irradiance, calculated with the RTM, can be assigned to this pixel dependent on the SZA. As a consequence not every pixel has to be processed with the radiative transfer model. An appropriate fitting function would reduce the needed RTM calculations to define the diurnal solar variation enormously.

Within this scheme a modified Lambert-Beer relation is used as fitting function in order to reduce the necessary RTM calculation for the estimation of the diurnal variation. This makes it possible to assign to each pixel the solar clear-sky irradiance with a small computation amount. Using the modified Lambert-Beer relation only two RTM calculations are necessary to calculate the complete diurnal variation for a given atmospheric state, hence for every day and region of 100x100 km (or later on 50x50 km) 2 RTM calculations are sufficient. It is important to note that even for cloudy sky situation 2 RTM calculation are enough to calculate the solar irradiance for the whole (e.g. 100x100 km) region, using the  $n-k$  relation (see equation 6).

Figure 1 provides an overview of the new scheme and the integrated use of the RTM within the clear sky scheme.

### 3.2 The fitting function

The Lambert-Beer relation is given by

$$I = I_0 * \exp(\tau) \quad (16)$$

where  $\tau$  is the optical depth

Considering path prolongation and projection to the earth surface leads to.

$$I = I_0 * \exp\left(\frac{\tau}{\cos(\theta_z)}\right) * \cos(\theta_z) \quad (17)$$

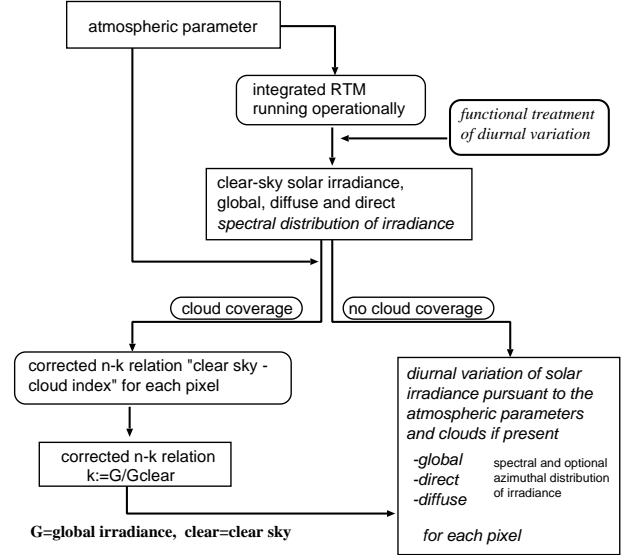


Figure 1: Overview of the new calculation scheme

This formula describes the behavior of the direct monochromatic radiation in the atmosphere, hence an effective optical depth  $\tau$  can be estimated for all SZA ( $\theta_z$ ).

$$\tau = \ln(I/I_0) \quad (18)$$

Using equation (18) for  $\theta_z=0$  leads to  $\tau_0$ . If we are dealing with **monochromatic radiation** then  $\tau$  is constant, hence  $\tau$  equals  $\tau_0$  for all SZA.

If we are dealing with **wavelength bands**  $\tau$  is not constant, but changes smoothly with increasing SZA.  $\tau_0$  is just the effective optical depth at  $\theta_z=0$ . The reason for that is the non-linear nature of the exponential function, for illustration (see Fig. 2).

Hence a correction of the optical depth, or equivalent to this, of the parameter  $\frac{\tau}{\cos(\theta_z)}$  is necessary.

$$I = I_0 * \exp\left(\frac{\tau}{\cos^a(\theta_z)}\right) * \cos(\theta_z) \quad (19)$$

Using this function the calculated direct radiation can be reproduced very well (see Fig. 6). The fitting parameter  $a$  is calculated based on two RTM calculations.

#### 3.2.1 Global irradiance

As explained above a correction of formula 17 is necessary for direct radiation if the formula is applied to wavelength bands, hence it is necessary for global radiation too. But in addition to the wavelength band effect the Lambert-Beer law is no longer "valid" for monochromatic radiation due to the effect of scattered photons that are "coming back". This effect is mainly described (considered) by the usage of the effective optical depth  $\tau_0$ . As a consequence, using the effective optical depth

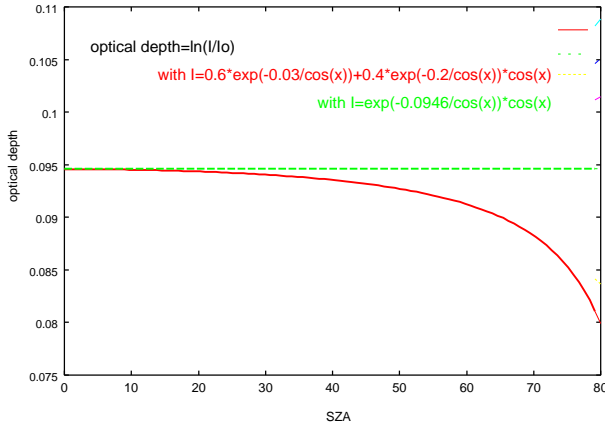


Figure 2: For illustration: A wavelength band is assumed to consist of two wavelengths, with an atmospheric optical depth of 0.03 at the one and an optical depth of 0.2 at the other. This results in an effective optical depth of 0.0946 for the wavelength band (whereby  $\tau$  is calculated using formula 18 at  $\text{SZA}=0$ ). Based on its definition the effective optical depth is  $-\ln(I/I_0)$  for all SZA, whereby  $I_0$  is the incoming irradiance and  $I$  the irradiance after the light has traveled through the atmosphere. It is obvious that the effective optical depth is changing with SZA if it is calculated as addition of monochromatic irradiances, whereas it is constant if the irradiance is treated as being monochromatic.

the Lambert-Beer is still a (relative) good approximation for “monochromatic” global radiation. But due to e.g. the atmospheric vertical inhomogeneity the change in the amount of photons coming back due to changes in SZA is not described by  $1/\cos(\theta_z)$  in detail. Hence a correction of formula 17 is necessary even for monochromatic incoming radiation, in order to yield a better match between RTM calculated and function values (see Fig. 3).

Since the Lambert-Beer relation, using the effective optical depth  $\tau_0$ , is still a (relative) good approximation if the incoming radiation is monochromatic, it is not so surprising that for wavelength bands the function

$$I_{\text{global}} = I_0 * \exp\left(\frac{\tau}{\cos^b(\theta_z)}\right) * \cos(\theta_z) \quad (20)$$

is (similar to the direct radiation case) also a good fitting function for global radiation (see Fig. 6).

### 3.2.2 Diffuse irradiance

The Lambert-Beer relation describes the attenuation of the incoming radiation. The incoming diffuse radiation at the top of the atmosphere is negligible. The source of the diffuse radiation is the attenuation of the direct radiation due to scattering processes. Hence the Lambert-Beer law is related to the irradiance of diffuse radiation but does not describe the irradiance of diffuse radiation, since dif-

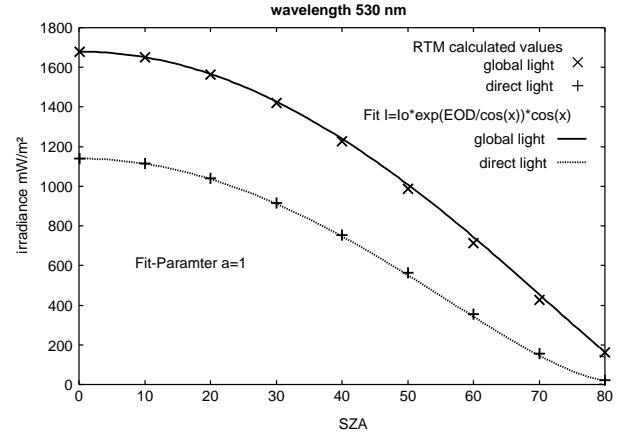


Figure 3: Illustration: For monochromatic radiation the Lambert-Beer relation is still a good approximation if the effective optical depth (EOD) is used. In order to yield a better match a correction of formula 17 (the Lambert-Beer relation) is necessary

fuse radiation can not be described in terms of attenuation of incoming radiation (see Fig. 4). Using the modified Lambert-Beer relation fitting works well for direct and global radiation. Consequently the diffuse irradiance could be calculated by subtracting the fit-results of the direct radiation from that of the global radiation. Hence it seems to be likely that a modified Lambert-Beer law is also usable for the fitting of diffuse radiation. Since the scaling with  $\cos(x)$  is not appropriate for diffuse radiation it is skipped and equation (21) is used for fitting.

$$I_{\text{diffuse}} = I_0 * \exp\left(\frac{\tau}{\cos(\theta_z)^c}\right) \quad (21)$$

This is the point of time to make one thing clear. The modified Lambert-Beer function is used as fitting function, its usage is physically motivated but in the end it is a fitting function. This is especially true for the case of diffuse radiation, since the Lambert-Beer law is no longer suitable for the description of monochromatic radiation, but fitting with the modified Lambert-Beer relation works very well (see Fig. 6).

### 3.2.3 General remarks

- At low visibilities (high optical depth, high aerosol load)  $I_0$  has to be enhanced for global and diffuse radiation.
- The fitting function has always the same appearance, just the fitting parameter  $a, b, c$  are different.
- The usage of the modified Lambert-Beer function is physically motivated, but it is actually a fitting function. In principle it is possible to fit the RTM calculations with any appropriate function for example a modified polynomial of third degree ( $a \cdot \cos^3(x) + b \cdot \cos^2(x) + c$ ) (see Fig.

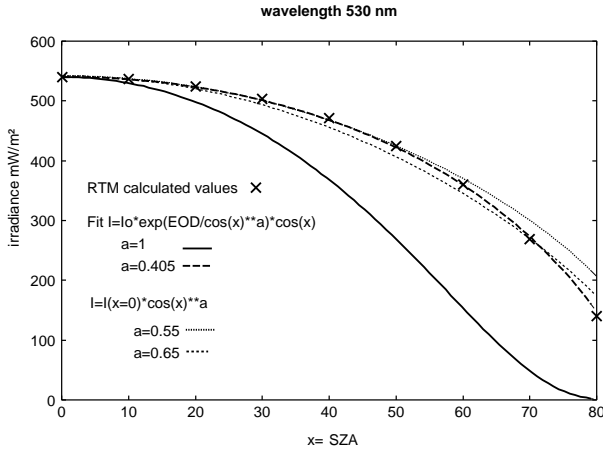


Figure 4: Since the modified Lambert-Beer relation does not describe the behavior of diffuse radiation, a correction of the Lambert-Beer relation is absolutely necessary. Fitting with a simple cosine relation lead to a much poorer agreement. (EOD=effective optical depth)

5). Hence the big advantage of the modified Lambert-Beer function is not the feasibility to fit the RTM calculations, but that it is possible to yield a very good match between fitted and calculated values by using only 2 SZA calculations. This is possible since the change of the irradiance with SZA is related to the Lambert-Beer law, hence using the modified Lambert-Beer relation “the degrees of freedom can be reduced”.

- The fitting function was tested for many different atmospheric states, e.g four different aerosol types, four different visibilities (5, 10, 23, 50), different water amounts, different standard atmospheres. Additionally it was tested that the fit also works if another RTM model (instead of libradtran) is used for the RTM calculations. There are no reasons to assume that there exist a atmospheric state for that the fit does not work very well. Hence it can be assumed that the fit works very well for all atmospheric states.
- For our purpose the sense of a appropriate fitting function is to save calculation time without losing “significant” accuracy. The question if a fitting function is usable for that purpose depends on the difference between the fitted values and the RTM calculated values (which are very small, less than 8W/m<sup>2</sup> below a SZA of 85 Deg.).

## 4 Conclusions

- Modified Lambert-Beer relation enables the integrated use of RTM within the Clear-Sky-Scheme.
- Modified Lambert-Beer law enables not only a com-

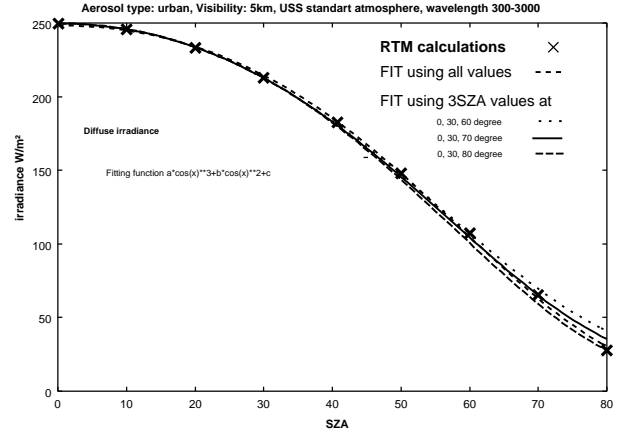


Figure 5: Comparison of the fit using a polynomial of third degree and the RTM calculations

puter time optimized fitting but also an easy handling look-up tables.

- It seems that deviations of the atmospheric state from the average ( $O_3$ ,  $H_2O$ , aerosols) can easily be corrected with the modified Lambert-Beer law. A correction of the effective optical depth  $\tau_0$ , whereas the a,b,c parameter remain unchanged, leads to a good match between RTM calculated and function values for  $H_2O$ . For aerosols similar tests have to be performed.
- Integrated use of RTM is linked with high flexibility relating to the input of the atmospheric state, changes in theory and the desirable output parameters.
- Spectral information is automatically provided, using the correlated-k option provided within the RTM libRadtran package (<http://www.libradtran.org/>). Optionally information about the azimuthal distribution of the diffuse radiation possible.
- Consistent calculations of global, direct and diffuse radiation for clear sky cases within one single scheme considering different aerosol types and not only turbidity are possible. Hence a improved estimation of the relation between diffuse and direct radiation is possible, especially for clear sky situations.
- Clear and easy linkage with cloudy sky scheme, whereas the treatment of the heterogenous cloud effects is not restricted. The improvement of the correction of heterogenous cloud effects is aimed for.
- Great parts of the well established Heliosat method can be adapted to the new scheme.



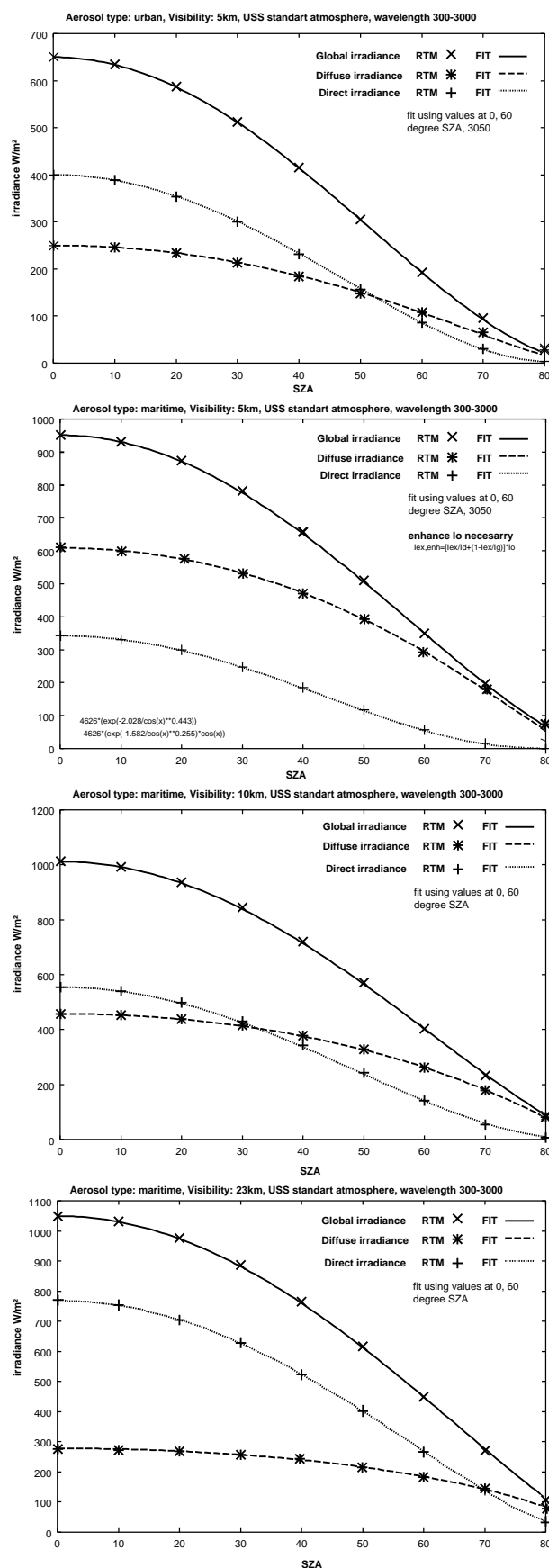


Figure 6: Comparison between RTM calculations and fit using the modified Lambert-Beer relation, for different atmospheric states

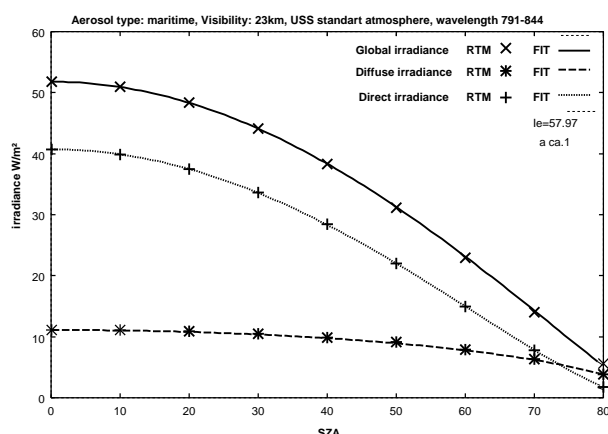


Figure 6a: Comparison between RTM calculations and fit using the modified Lambert-Beer relation. Example for fit within a small wavelength band

## ACKNOWLEDGEMENTS:

This work is funded by the EC (NNK5-CT-200-00322). For providing the libRadtran RTM package we thank: Arve Kylling (NILU) and Bernhard Meyer (DLR).

## REFERENCES

- Beyer, H.G., Constanzo, C. & Heinemann, D., *Modifications of the Heliosat procedure for irradiance estimates from satellite data*, Solar Energy, 1996, 56, 207-121
- Bourges, B., *Yearly variations of the Linke turbidity factor*, Climatic Data Handbook of Europe, Kluwer Academic Publishers, Dordrecht, 1992, 61-64
- Cano, D., Monget, J.M., Albuissou, M., Guillard, H., Regas, N. & Wald, L., *A method for the determination of the global solar radiation from meteorological satellite data*, Solar Energy, 1986, 37, pp 31-39
- Dumortier, D., *Modelling global and diffuse horizontal irradiances under cloudless skies with different turbidities*, Daylight II, JOU2-CT92-0144, Final Report Vol. 2, 1995
- Commission of the European Communities, *Green Paper: Towards a European strategy for the security of energy supply*, 2000
- Hammer, Annette, *Anwendungsspezifische Solarstrahlungsinformationen aus Meteosat-Daten*, Carl von Ossietzky University of Oldenburg, Faculty of Physics, 2000, Ph.D. Thesis
- Page, J., *Algorithms for the Satellight programme*, 1996
- Kasten, F. & Young, A.T., *Revised optical air mass tables and approximations formula*, Applied Optics, 1989, 28, 4735-4738
- Kasten, F., *The Linke turbidity factor based on improved values of the integral Rayleigh optical thickness*, Solar Energy, 1996, 56, pp 239-244
- Hammer, A., Heinemann, D. & Hoyer, C., *Effect of Meteosat VIS Sensor Properties on Cloud Reflectivity*, institution=University of Oldenburg, Third SoDa meeting, Bern (CH), 2001
- Skartveit, A., Olseth, J.A. & Tuft, M.E., *An hourly diffuse fraction model with correction for variability and surface albedo*, Solar Energy, 1998, 63, 173-183
- Zelenka, A., Perez, R., Seals R. & Renne, D., *Effective accuracy of satellite-derived hourly irradiances*, Theoretical and Applied Climatology, 1999, 62, 199-207